RSAC 2025 Conference

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SESSION ID: BR-W01

Provable Security for End-to-End Encrypted Cloud Storage

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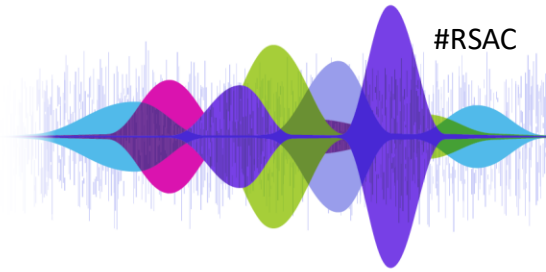

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Provable Security for E2EE Cloud Storage

A Formal Treatment of End-to-End Encrypted Cloud Storage

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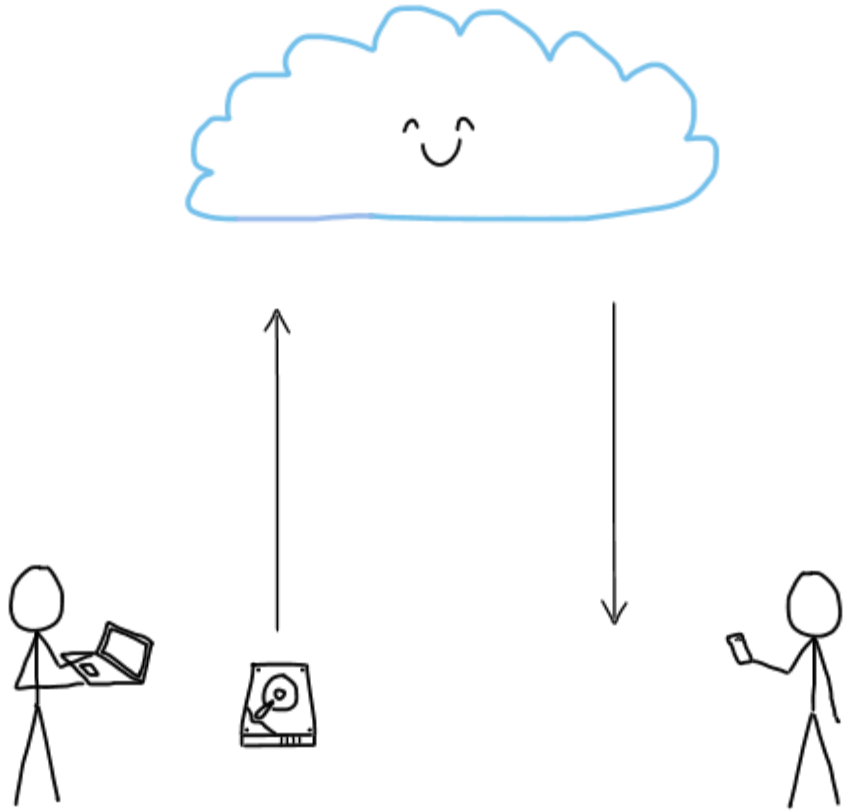
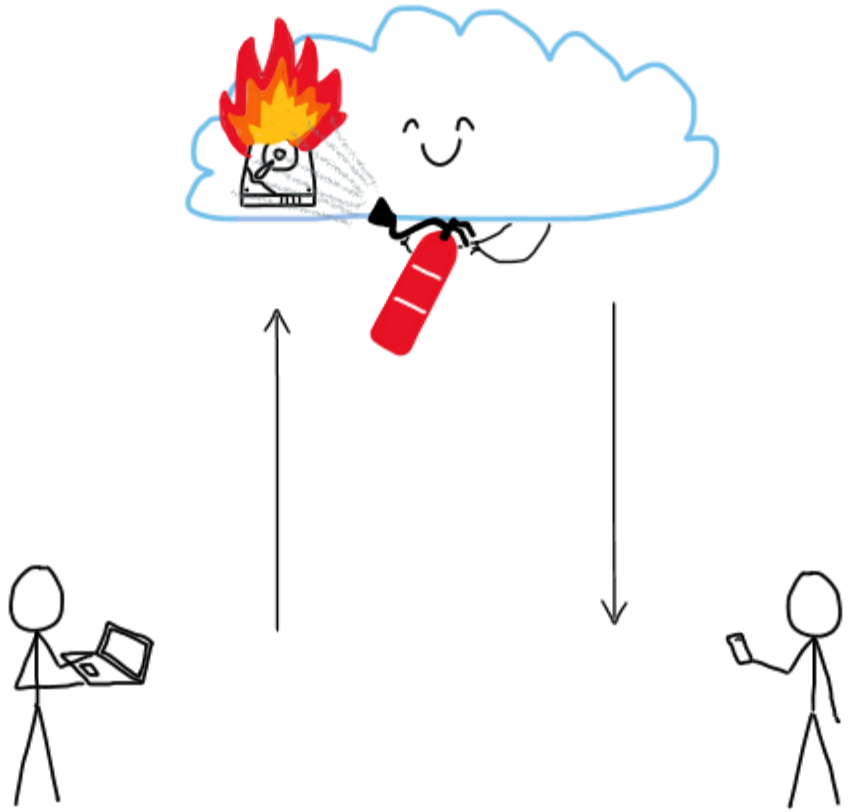
Cloud Storage

- Benefits:
  - Availability



Cloud Storage

- Benefits:
  - Availability
  - Redundancy



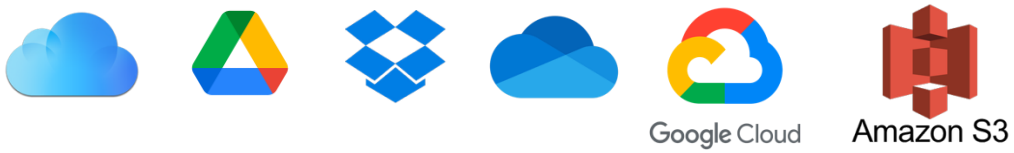
Cloud Storage

- Benefits:
  - Availability
  - Redundancy
  - Scalability

[1] https://cybersecurityventures.com/the-world-will-store-200-zettabytes-of-data-by-2025/ (Sausalito, Calif., Feb. 1, 2024)

Cloud Storage

- Benefits:
  - + Availability
  - + Redundancy
  - + Scalability
- Concerns:
  - - Data leaks

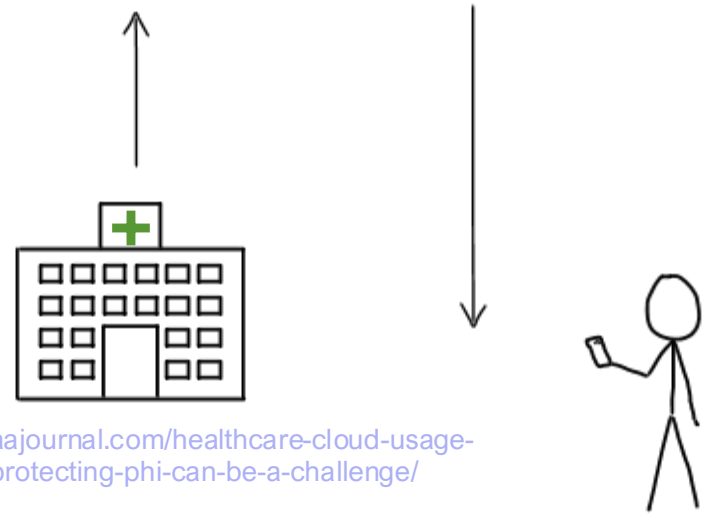


4 of 5

Americans had private information exposed at least once [2]

+381%

Data breaches [2]



https://www.hipaajournal.com/healthcare-cloud-usage-grows-but-protecting-phi-can-be-a-challenge/

[2] https://www.apple.com/newsroom/pdfs/The-Rising-Threat-to-Consumer-Data-in-the-Cloud.pdf (December 2022)

Cloud Storage

- Benefits:
  - + Availability
  - + Redundancy
  - + Scalability
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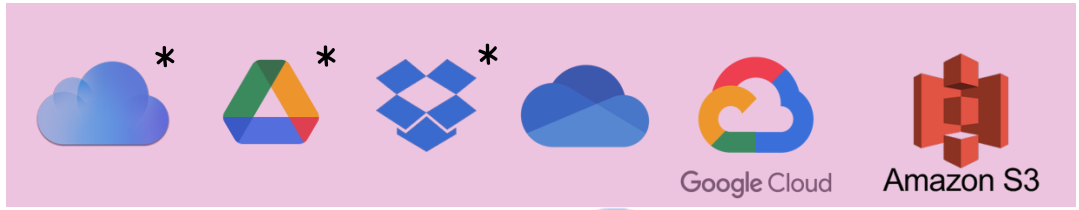
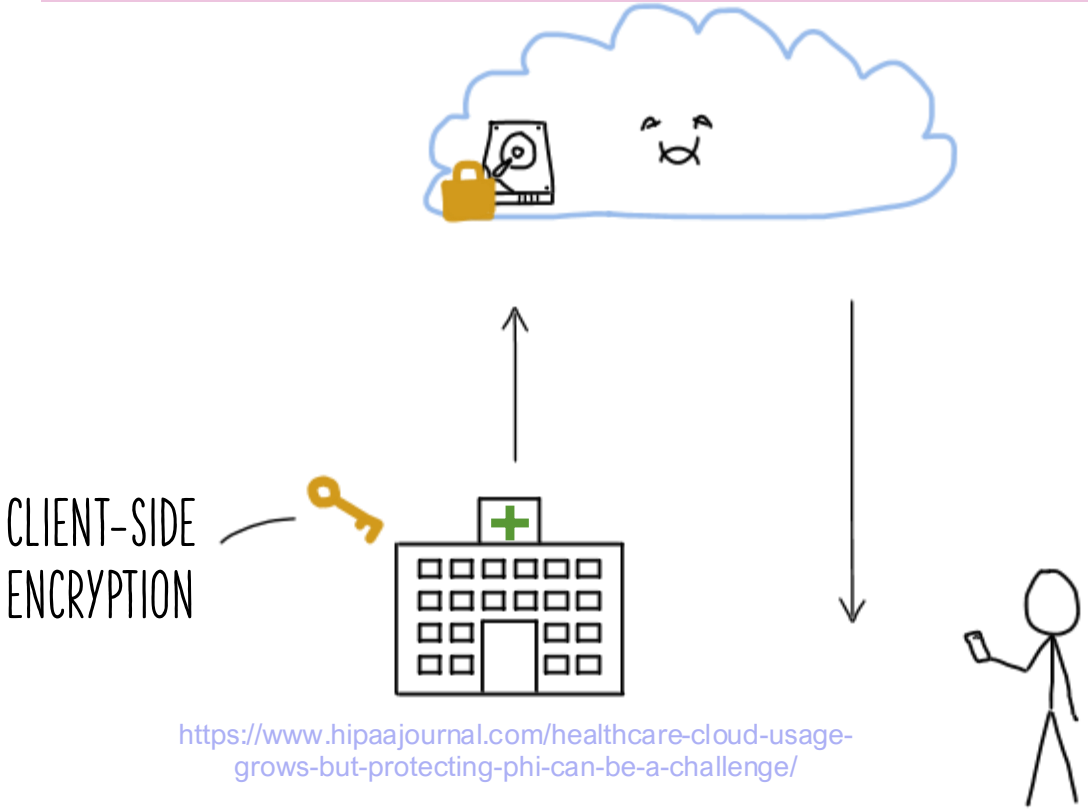


no E2EE
by default
*OPTIONAL AND LIMITED E2EE



https://www.hipaajournal.com/healthcare-cloud-usage-grows-but-protecting-phi-can-be-a-challenge/

E2EE Cloud Storage Providers

"WITH **MEGA**, YOU CONTROL THE ENCRYPTION"

300 MILLION USERS

MEGA

INSECURE!

[BHP23] [AHMP23]

AMNESTY INTERNATIONAL, GERMAN GOVERNMENT

"ULTIMATE SECURITY"

Nextcloud

INSECURE!

[ABCP23]

"EXCEPTIONALLY PRIVATE CLOUD"

sync.com

"EUROPE'S MOST SECURE CLOUD STORAGE"

pCloud

INSECURE!

icedrive

"THE STRONGEST ENCRYPTED CLOUD STORAGE IN THE WORLD"

Seafile

"SUPPORTS CLIENT-SIDE END-TO-END ENCRYPTION"

[HT24]

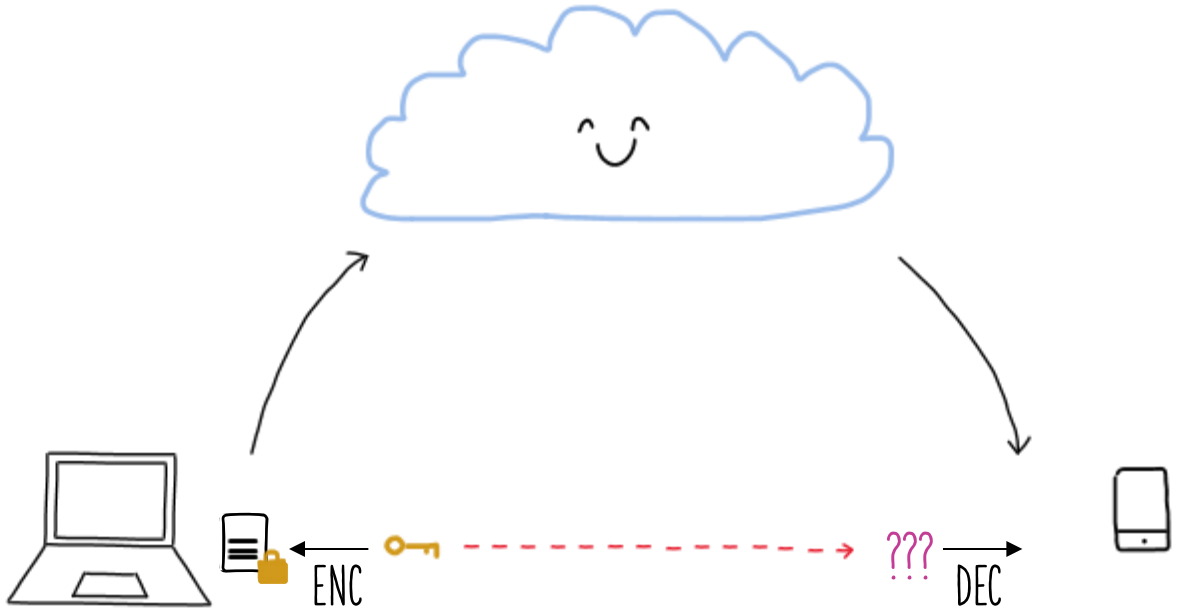
"FREE, ENCRYPTED, AND SECURE CLOUD STORAGE. YOUR PRIVACY, SECURED BY MATH"

Proton Drive

NOT PROVABLY SECURE [M24]

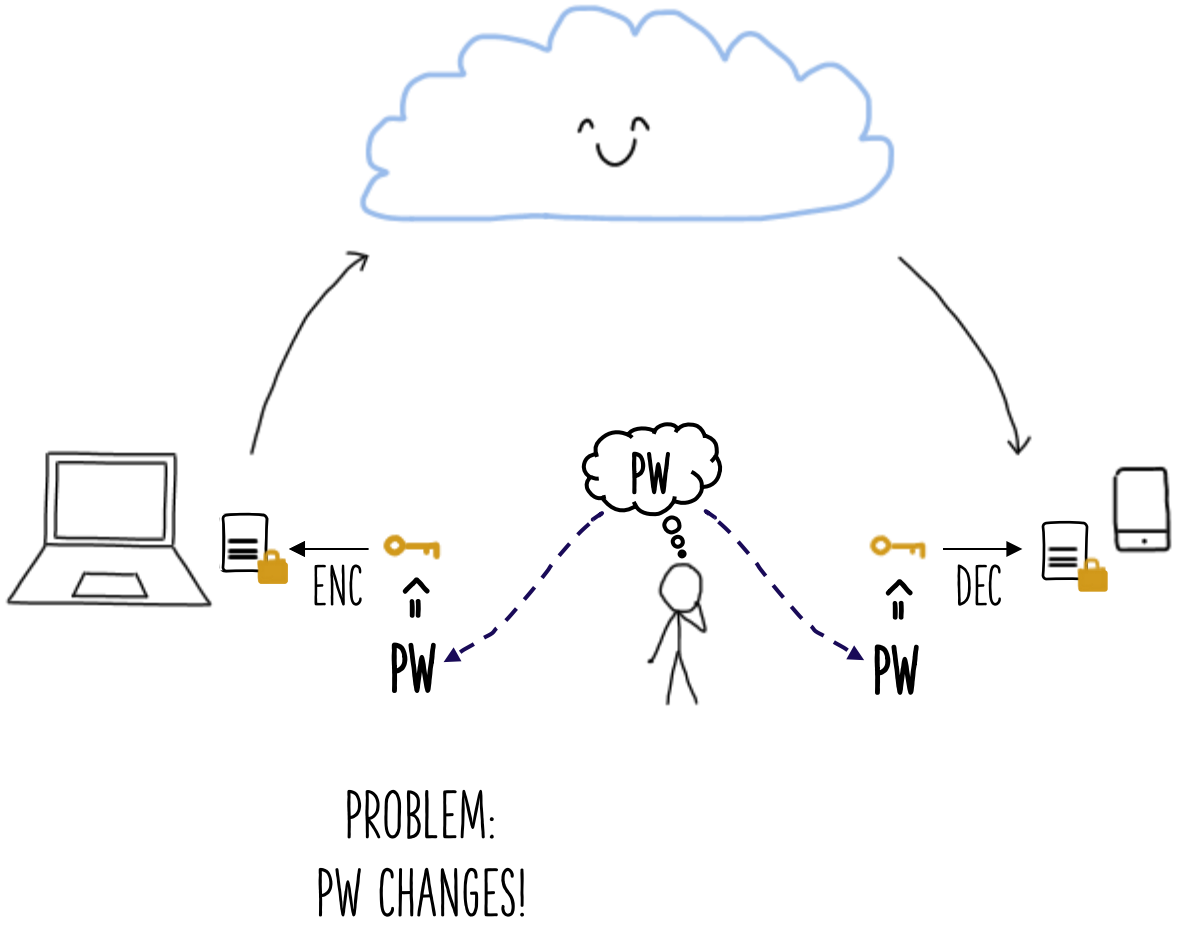
Why Is It Hard?

1. key distribution



Why Is It Hard?

1. key distribution
2. password-based security



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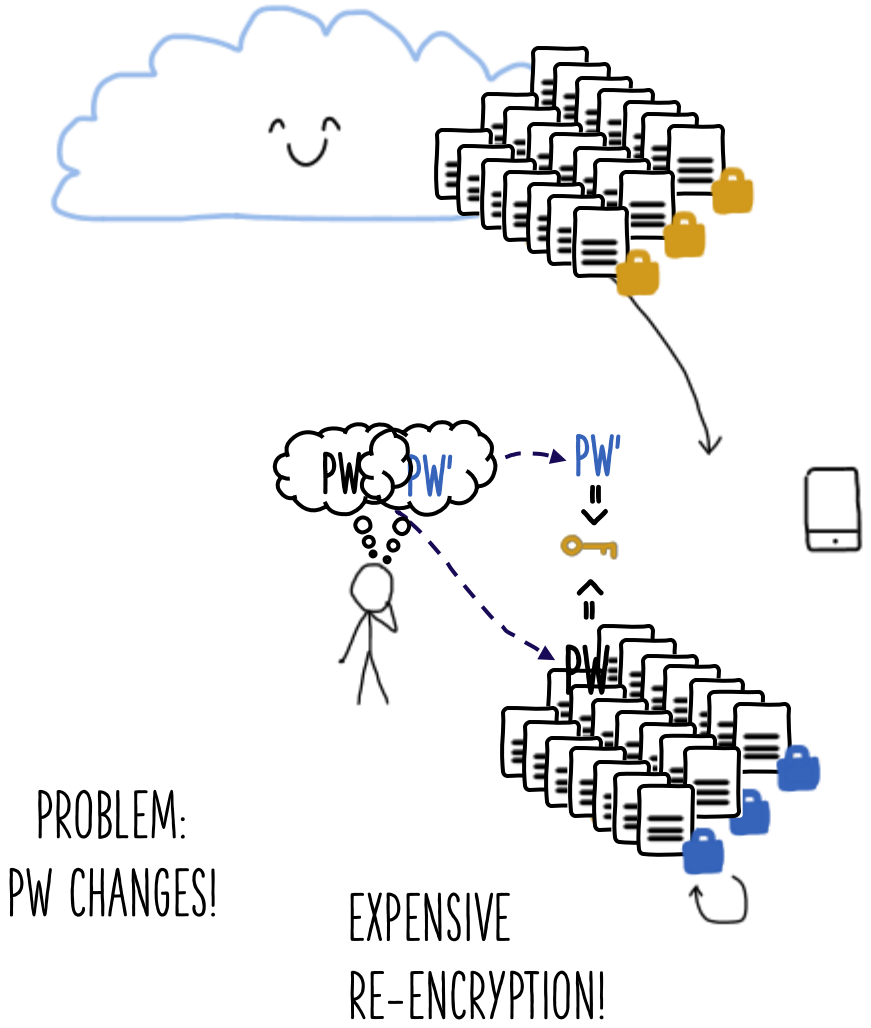
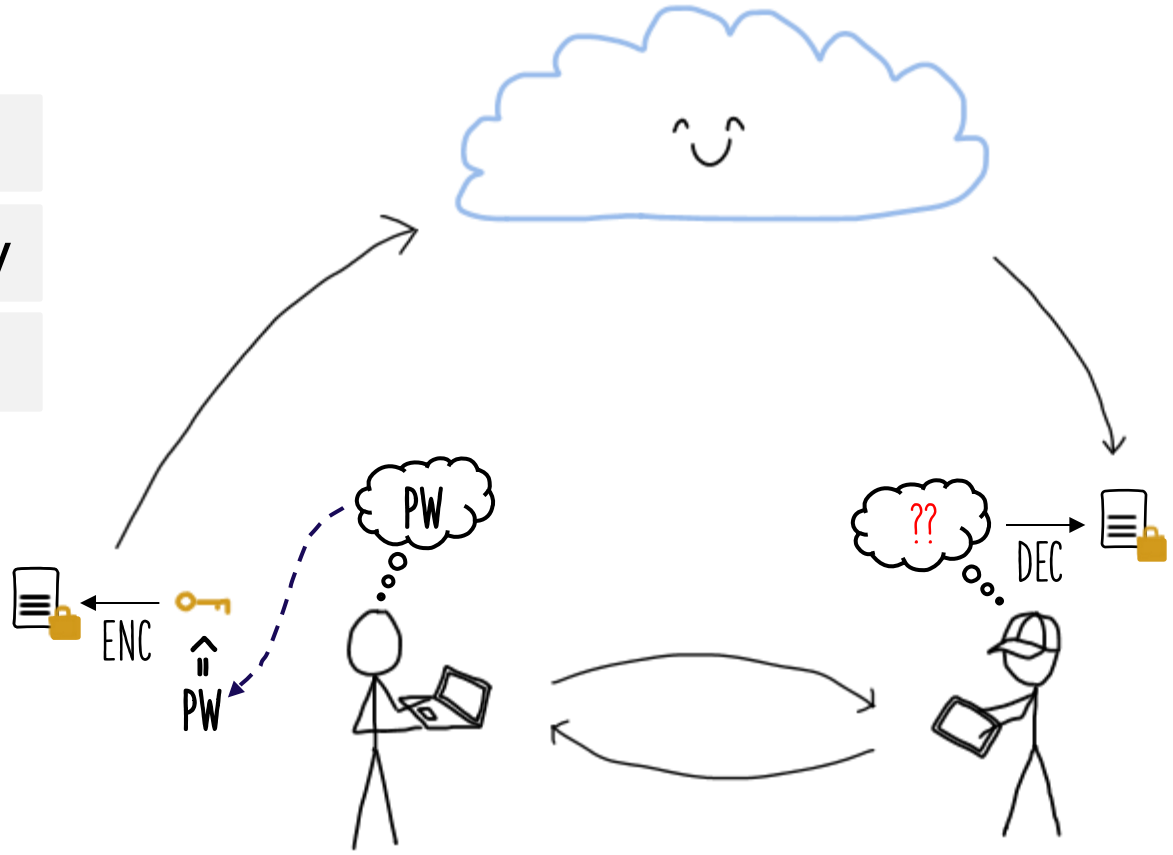
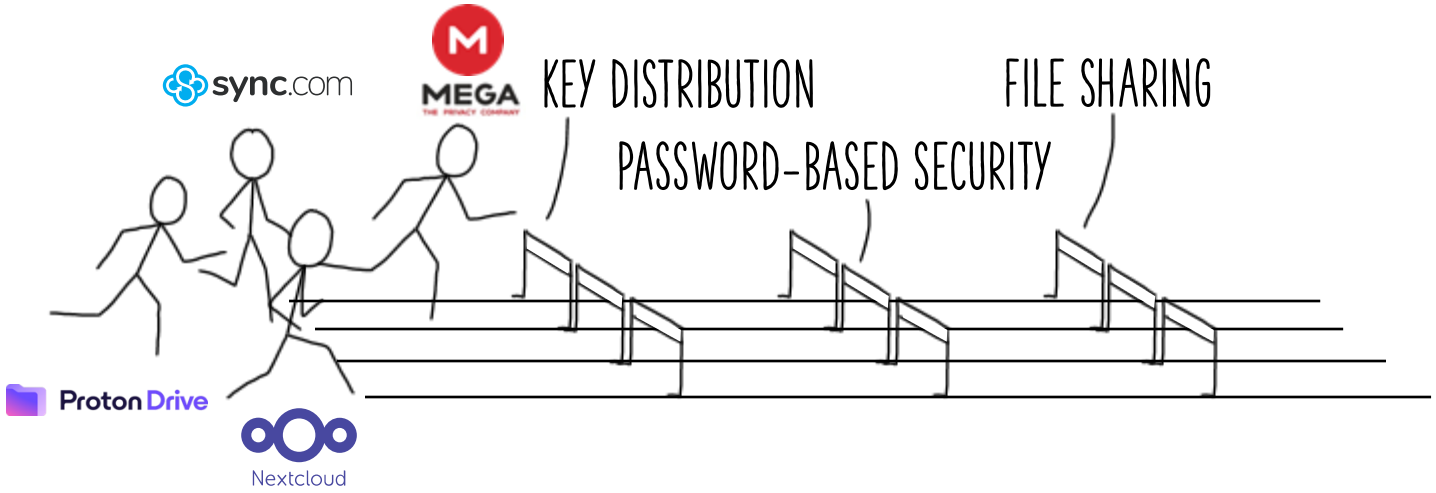


Why Is It Hard?

1. key distribution
2. password-based security
3. file sharing



Why Is It *Actually* Hard?



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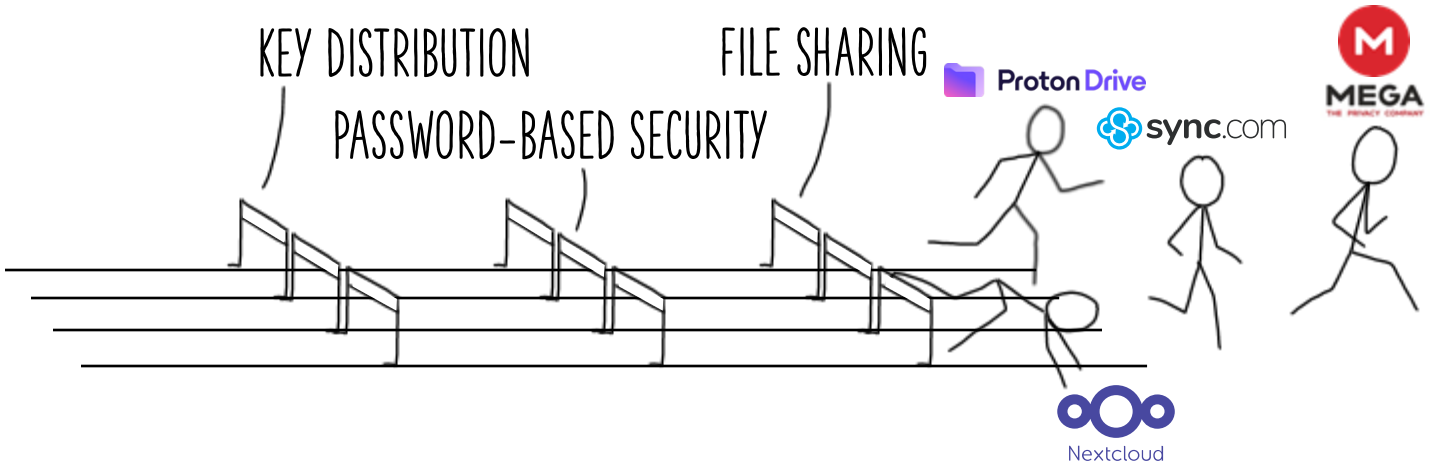

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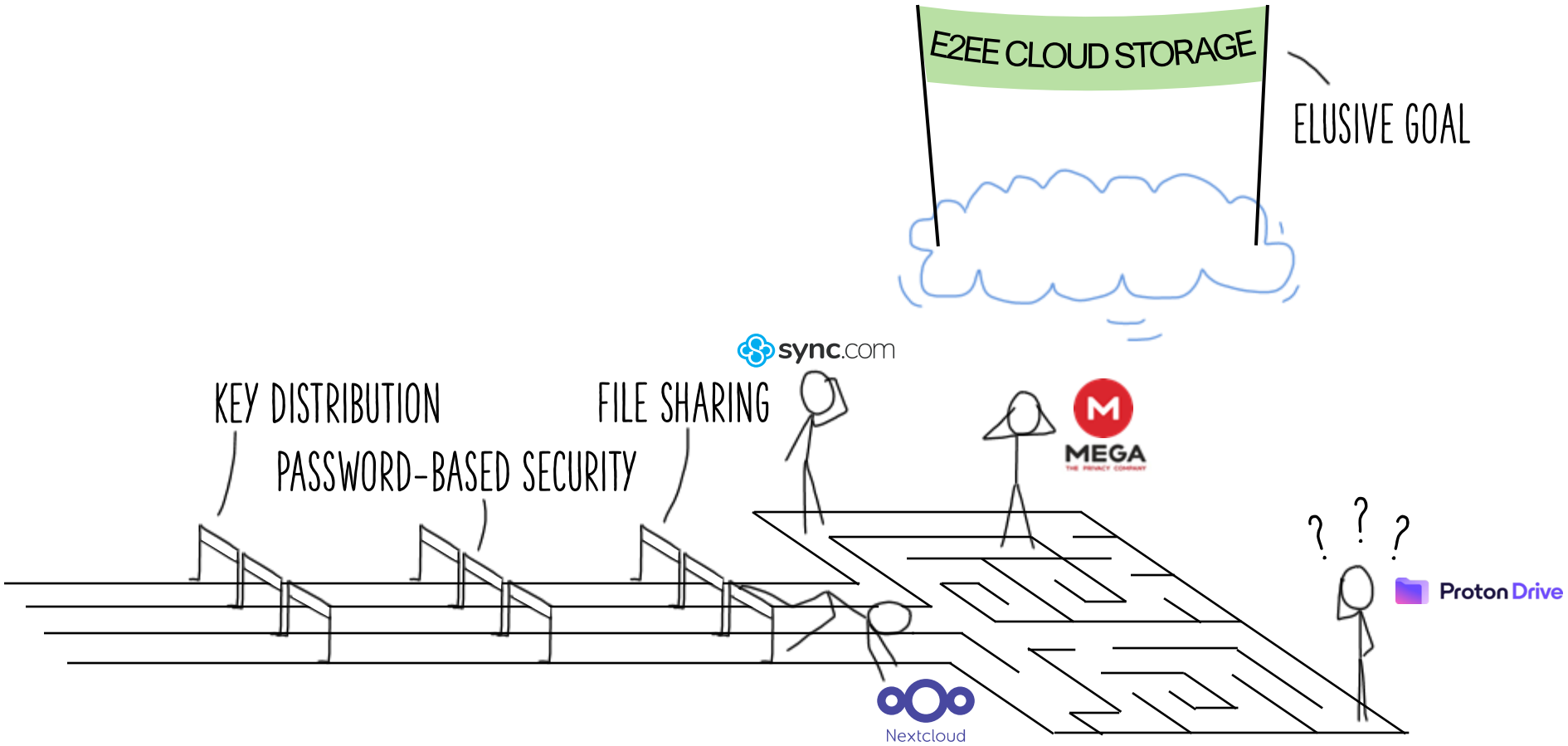
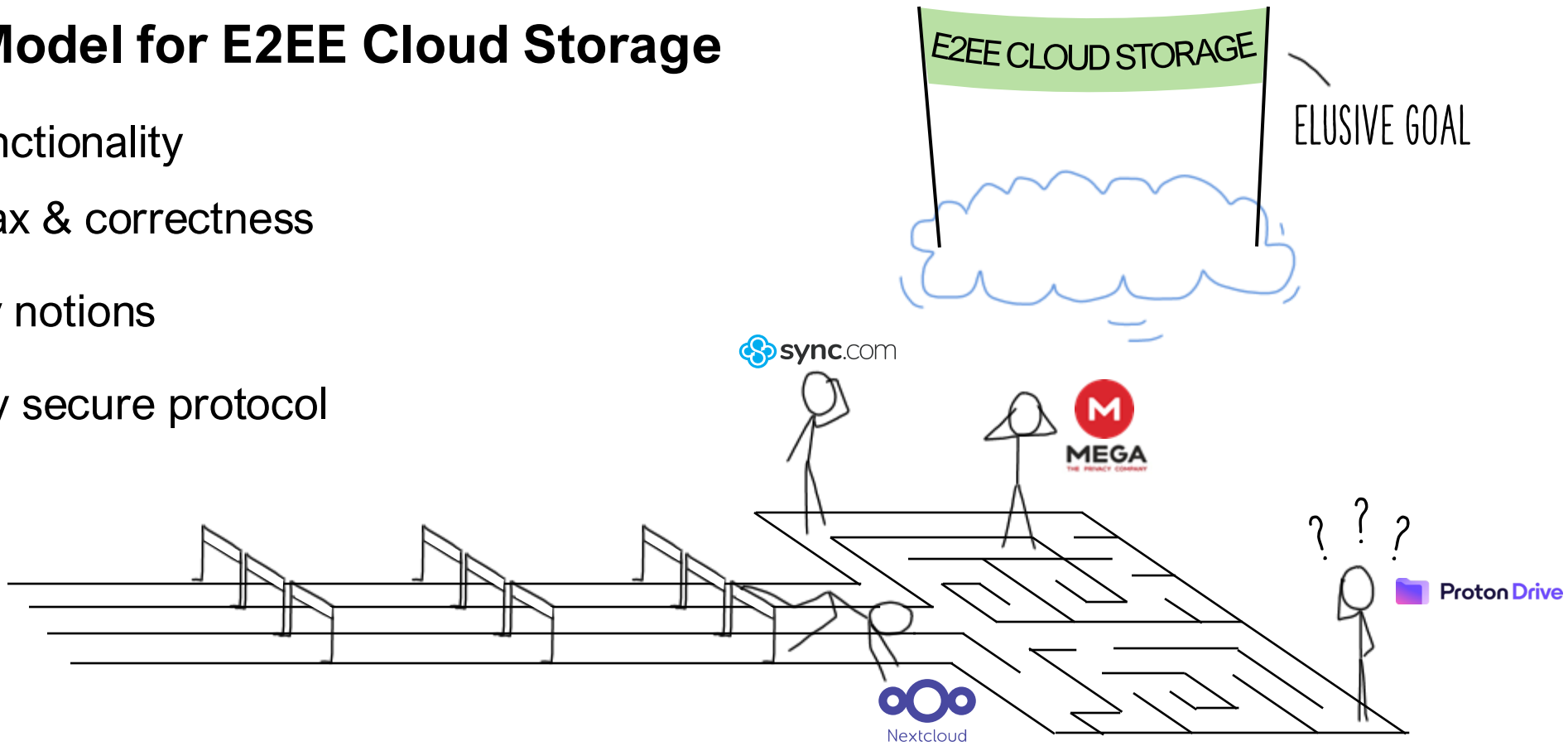


Our Work

Formal Model for E2EE Cloud Storage

- Core functionality
  - → Syntax & correctness
- Security notions
- Provably secure protocol



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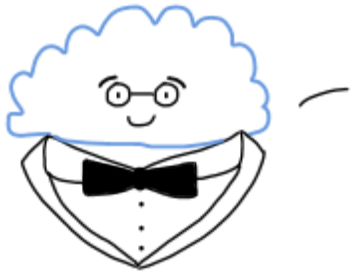
Formalizing E2EE Cloud Storage

Syntax and Security

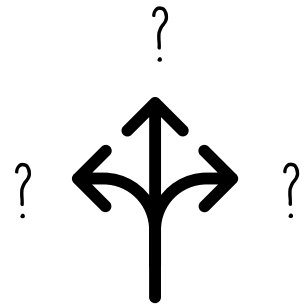
Formalizing E2EE Cloud Storage

Model Goals



ALL MODELS ARE WRONG,
BUT SOME ARE USEFUL!

MEGA
Nextcloud
Proton Drive
sync.com
icedrive
pCloud
Seafile



Capture existing systems

1 Expressive

Capture *real-world* systems

2 Faithful

Capture future systems

3 Generic

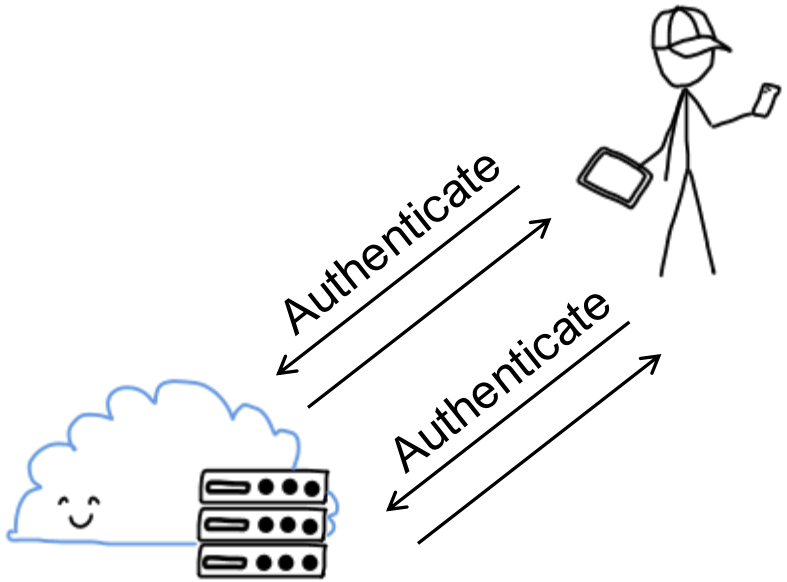
Syntax "WHAT MAKES A CLOUD STORAGE A CLOUD STORAGE?"

Core Functionality

1 EXPRESSIVE

- Register (create account)
- Authenticate (log in)
- Put (upload a file)
- Update (modify content)
- Get (download)
- Share
- Accept (receive share)

INTERACTIVE PROTOCOLS

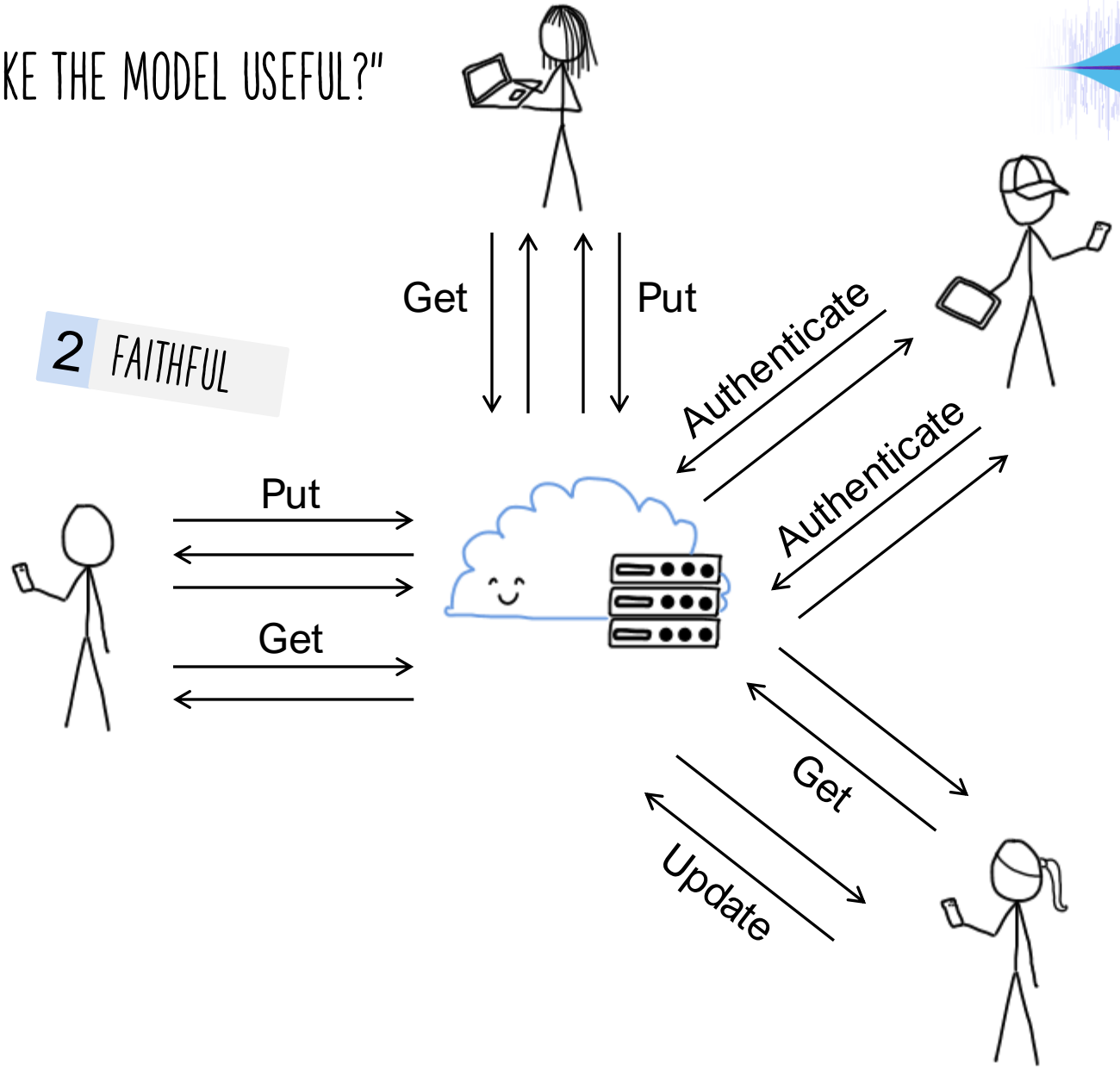


Syntax "How do we make the model useful?"

Model Choices

- Arbitrary interleaving

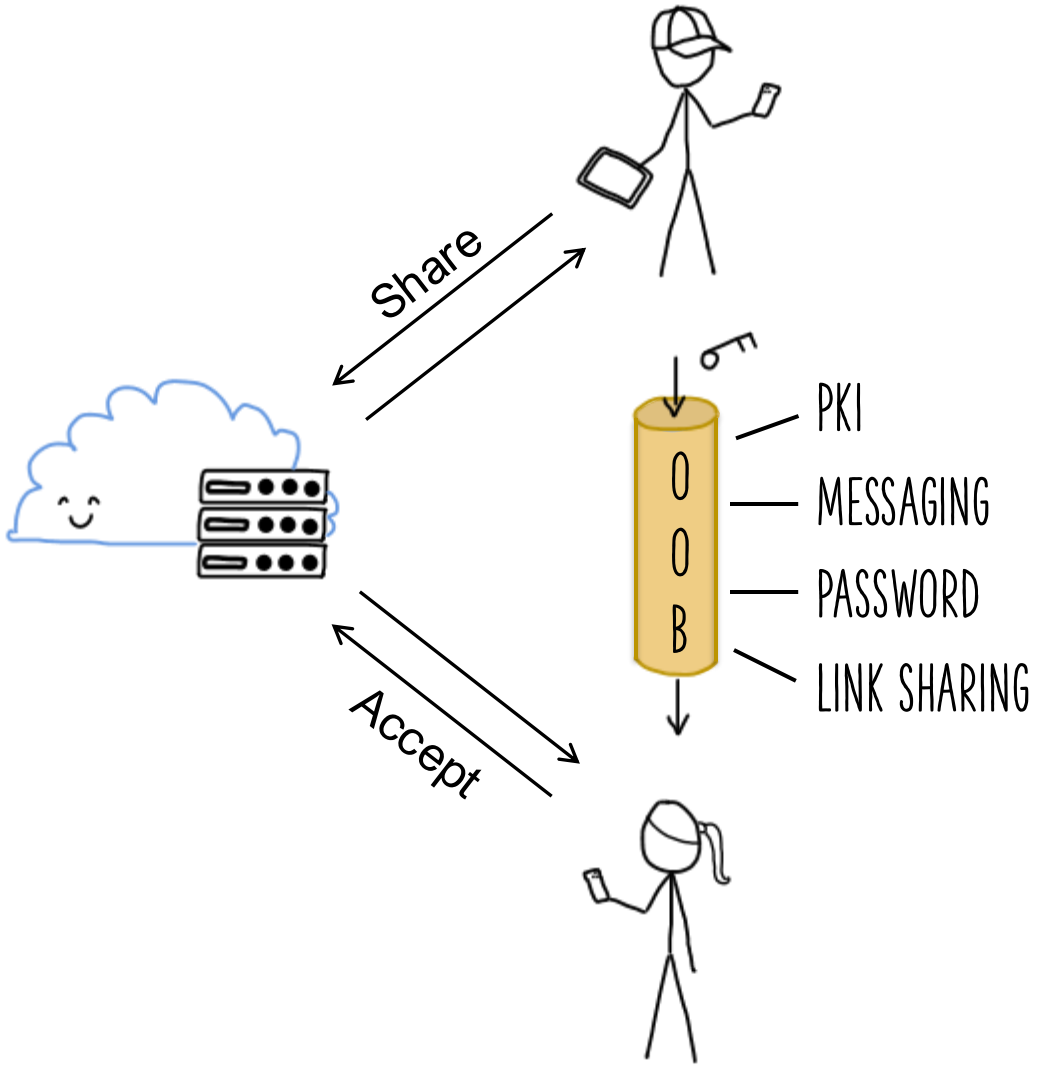
2 FAITHFUL



Syntax "How do we make the model useful?"

Model Choices

- Arbitrary interleaving — 2 FAITHFUL
- Abstract OOB channel for sharing — 3 GENERIC



Security

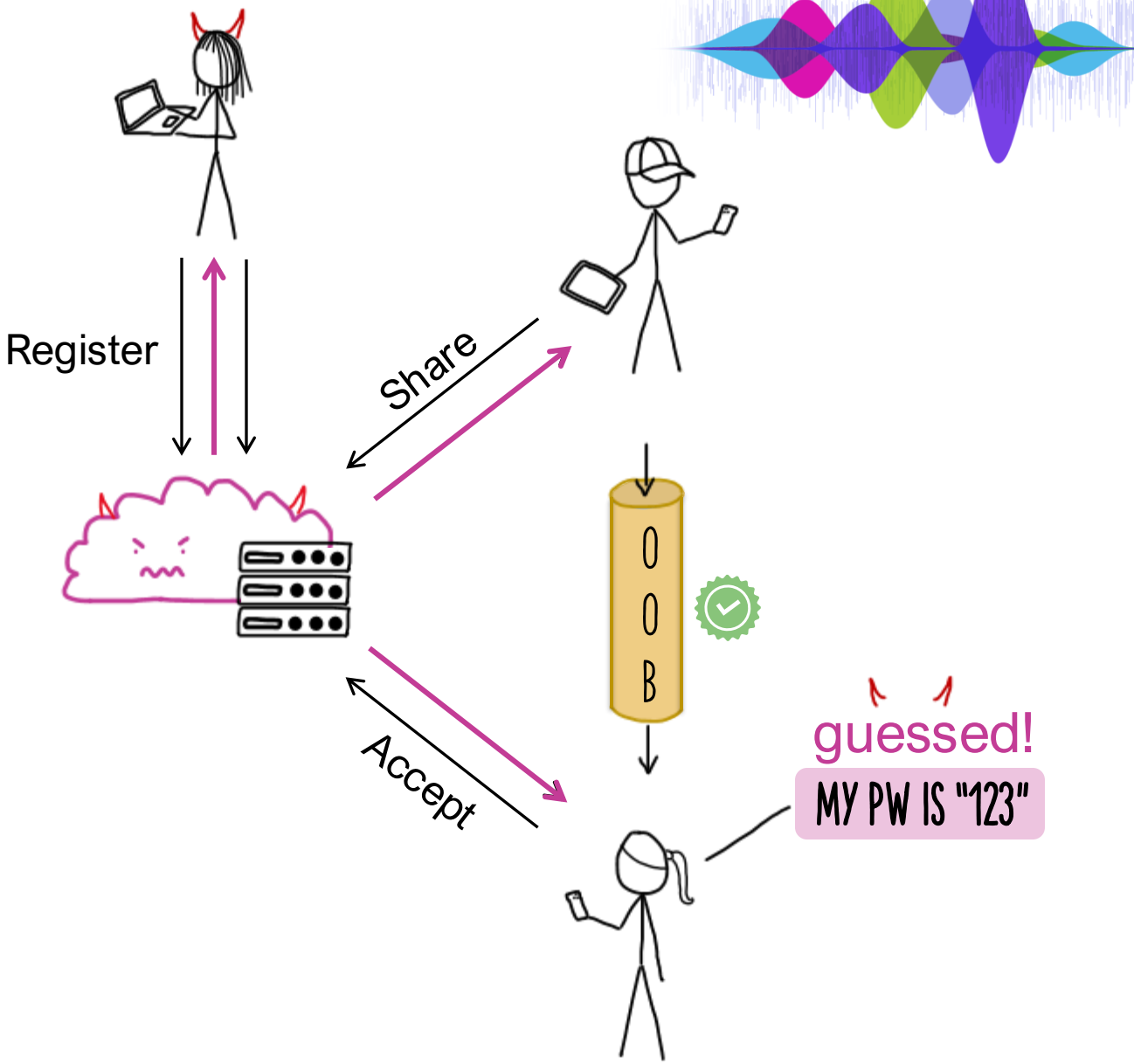
Threat model

- Malicious cloud provider
- Trusted OOB channel

Adversary capabilities

- Control honest client protocol steps
- Guess honest user passwords
- Compromise users

SELECTIVE AND ADAPTIVE



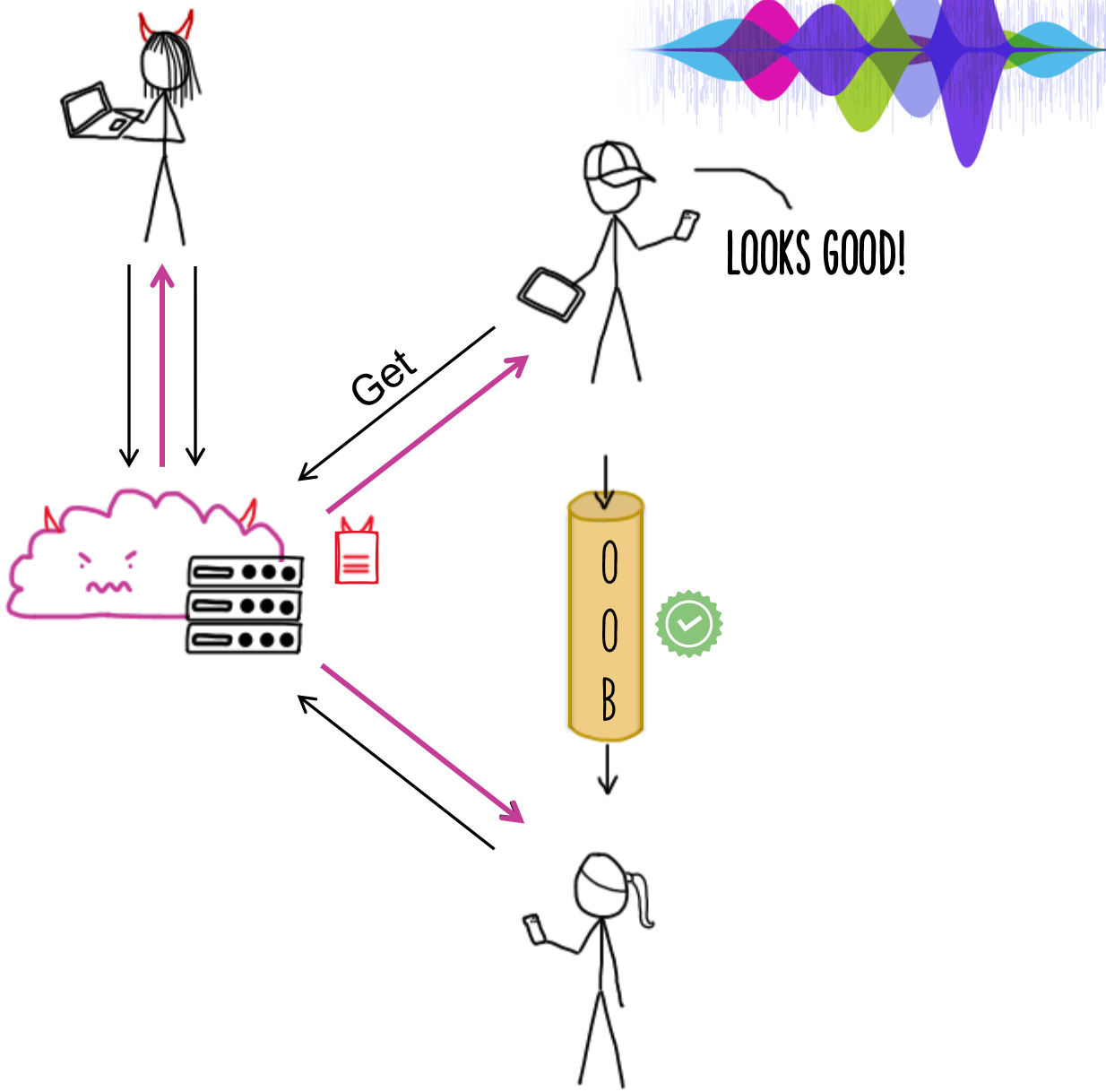
Security "GAME-BASED SECURITY NOTIONS"

To win a game and break security, the adversary must, for an honest user, …

Integrity

- … inject/modify a file.

INT-PTXT-STYLE GAME



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Security "GAME-BASED SECURITY NOTIONS"

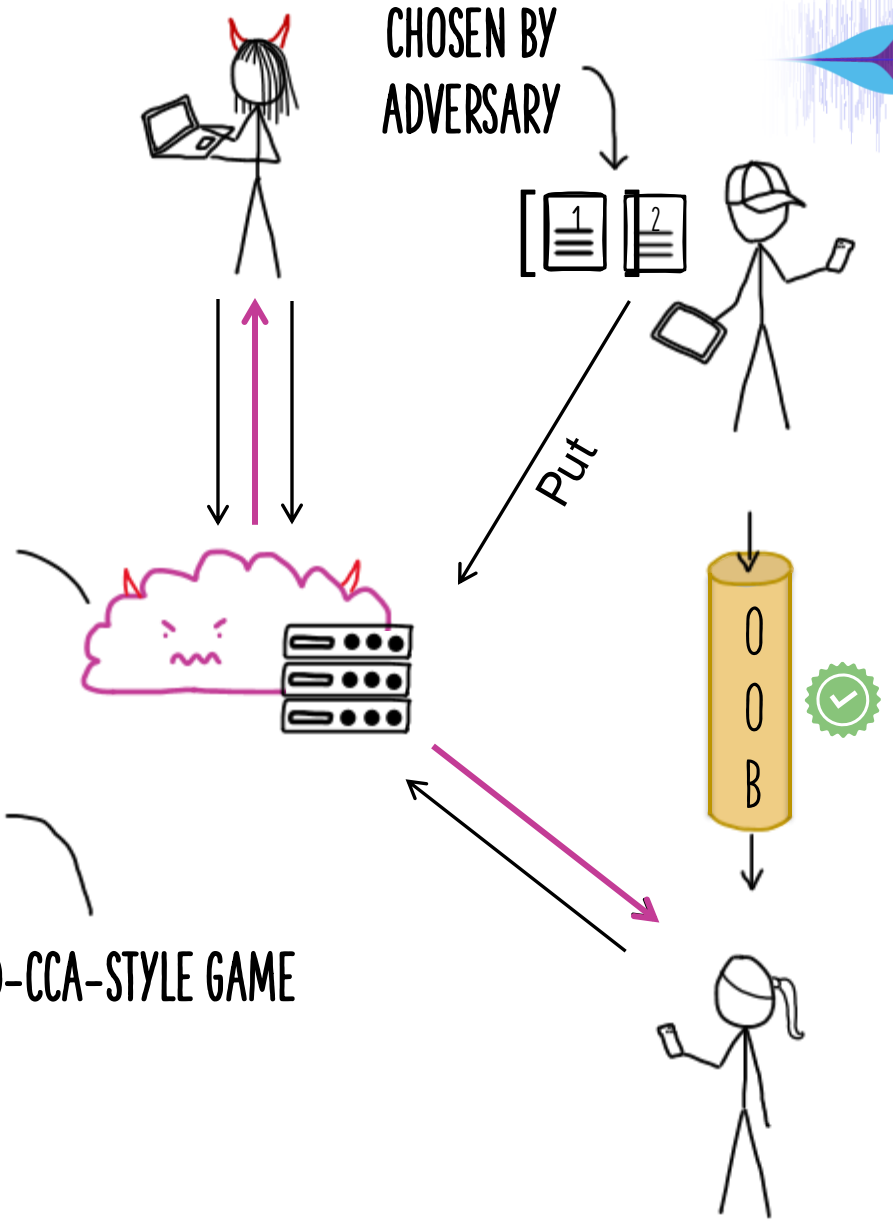
To win a game and break security, the adversary must, for an honest user, …

Integrity

- … inject/modify a file.

Confidentiality

- … distinguish uploaded chosen files



Security "GAME-BASED SECURITY NOTIONS"

To win a game and break security, the adversary must, for an honest user, …

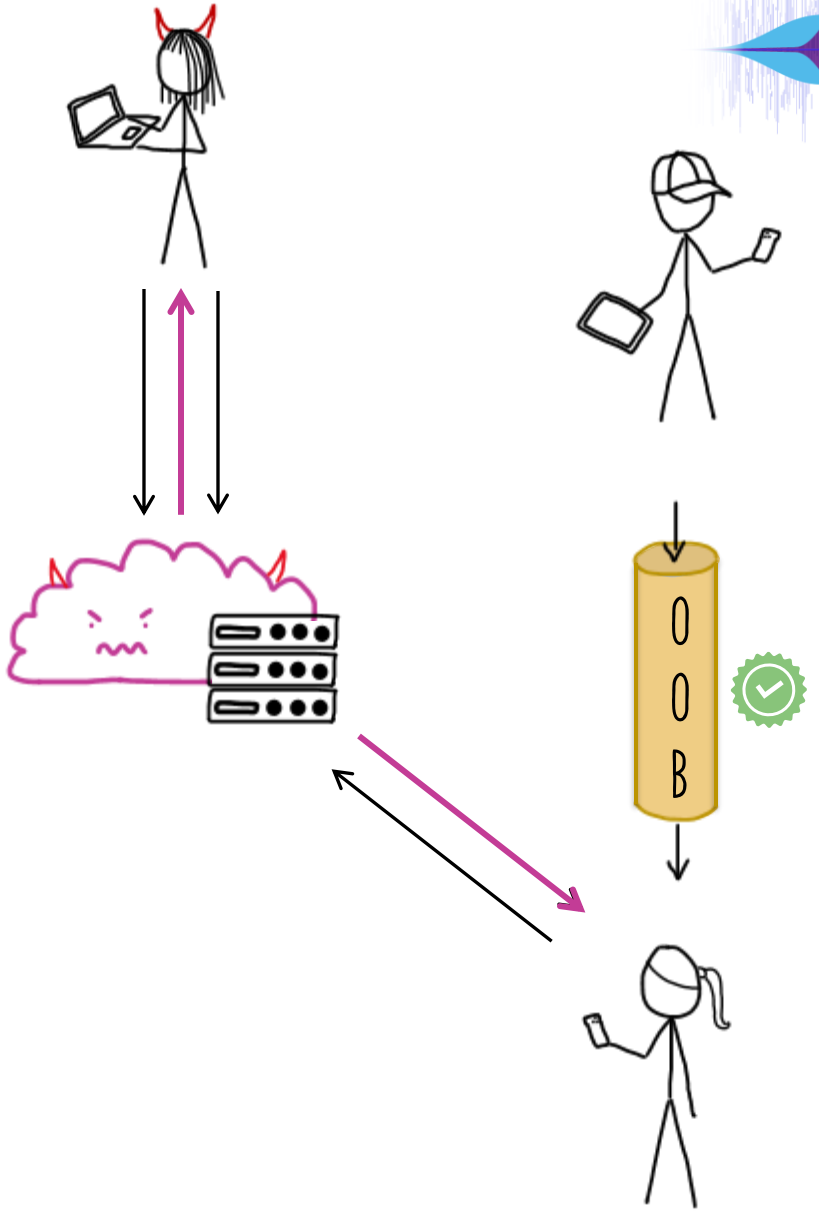
Integrity

- … inject/modify a file.

Confidentiality

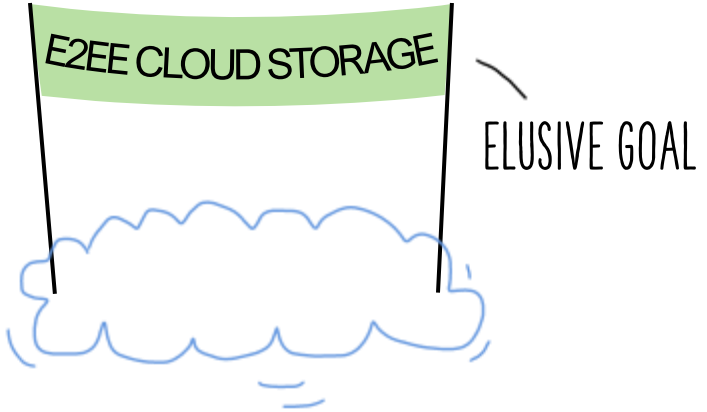
- … distinguish uploaded chosen files

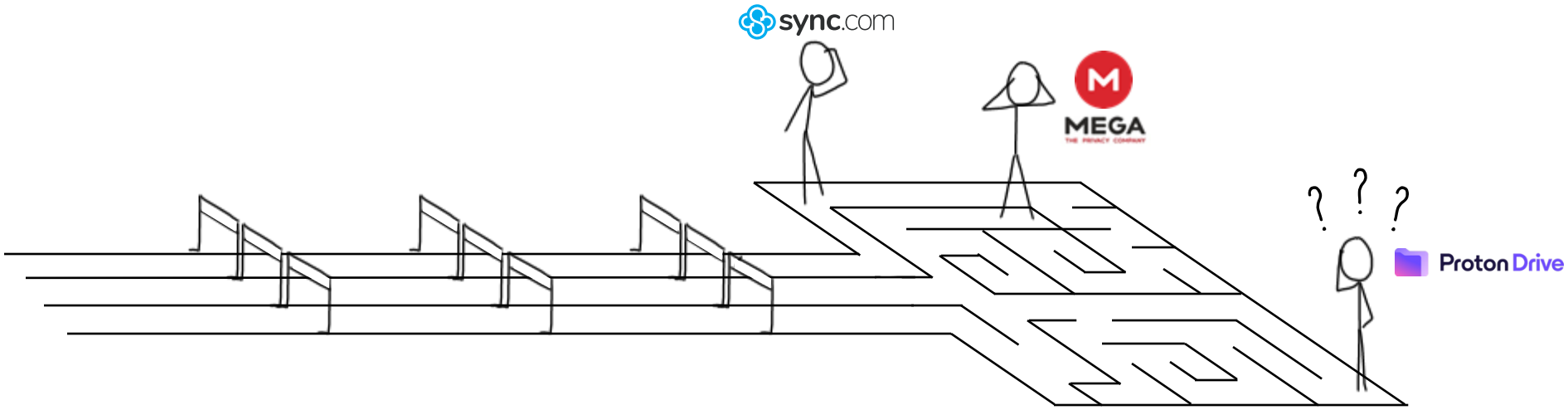
Secure = ”low” winning probability



Problem solved?

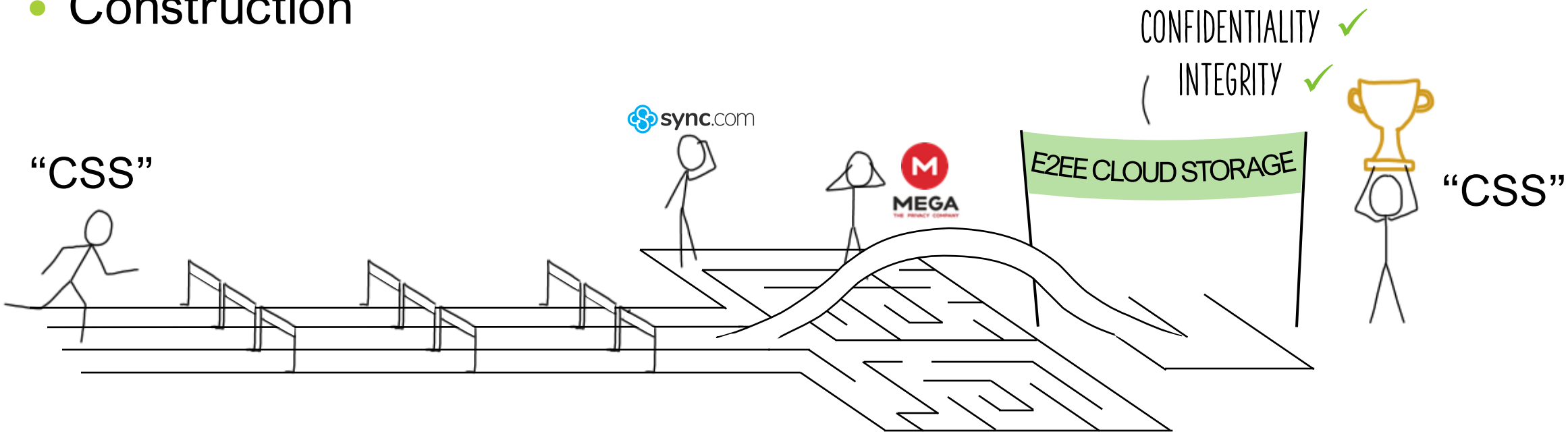
- Syntax ✓
- Security notions ✓





Problem solved?

- Syntax ✓
- Security notions ✓
- Construction



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Constructing E2EE Cloud Storage

CSS (Cloud Storage Scheme)

INTERACTIVE MULTI-STEP PROTOCOLS

Challenges

1. key distribution
2. pw-based security
3. file sharing

Core Functionality

- Register (create account)
- Authenticate (log in)
- Put (upload a file)
- Update (modify content)
- Get (download)
- Share
- Accept (receive share)

Threat Model

- Malicious server

- Trusted OOB channel

CSS: Building Blocks

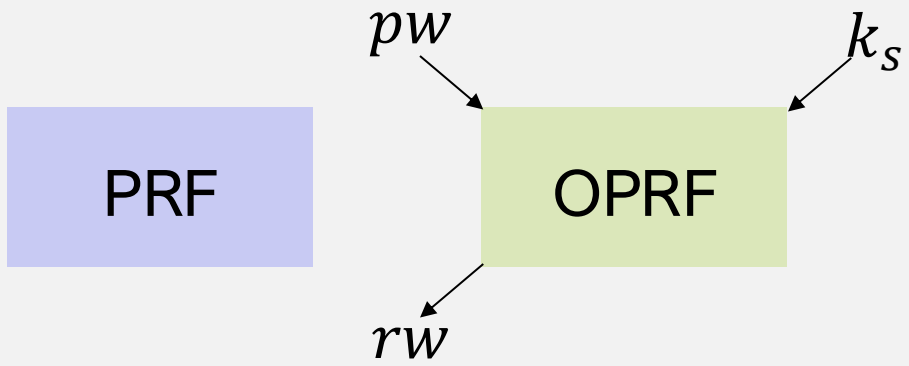
Pseudo-Random Function

PRF

for key derivation

CSS: Building Blocks

(OBLIVIOUS) Pseudo-Random Function



for key derivation

(INTERACTIVE)

Authenticated Encryption

AEAD

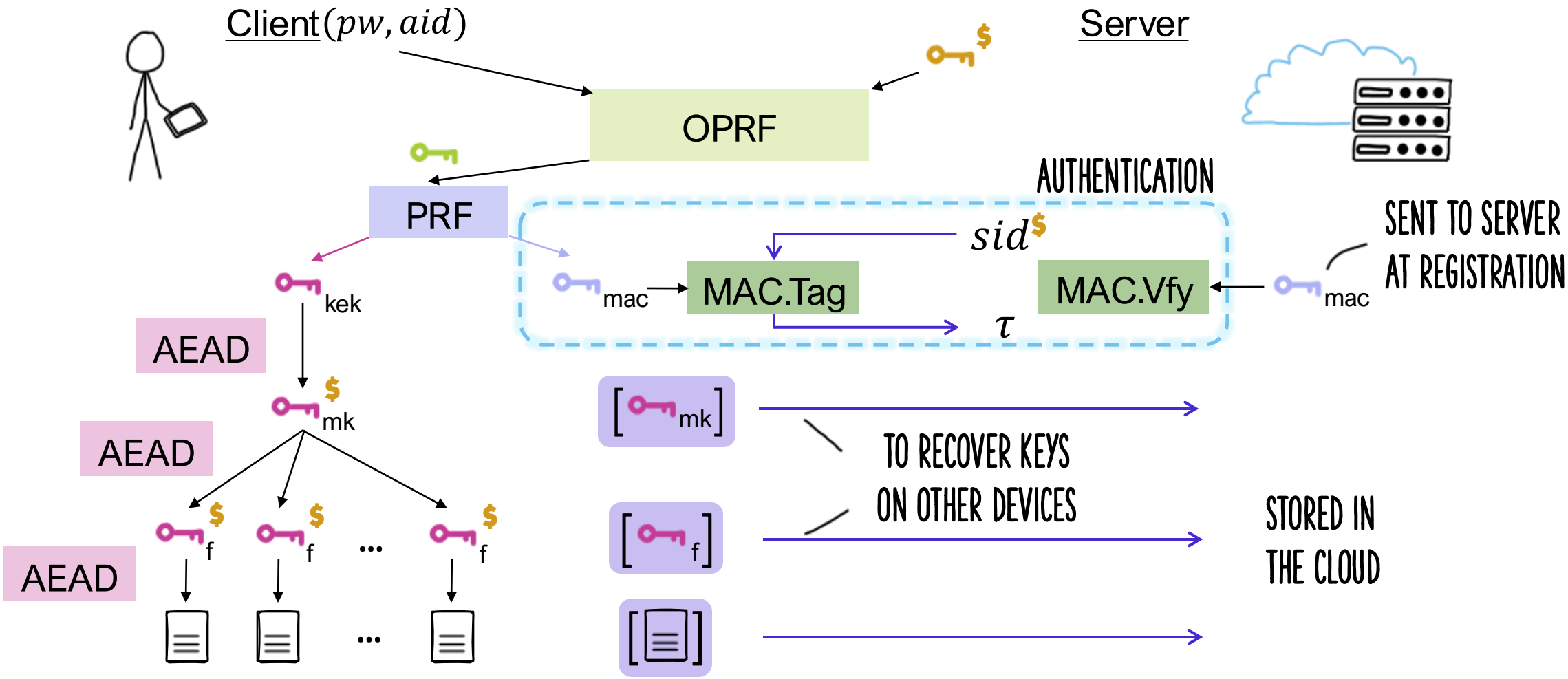
for data confidentiality and integrity

Message Authentication Code

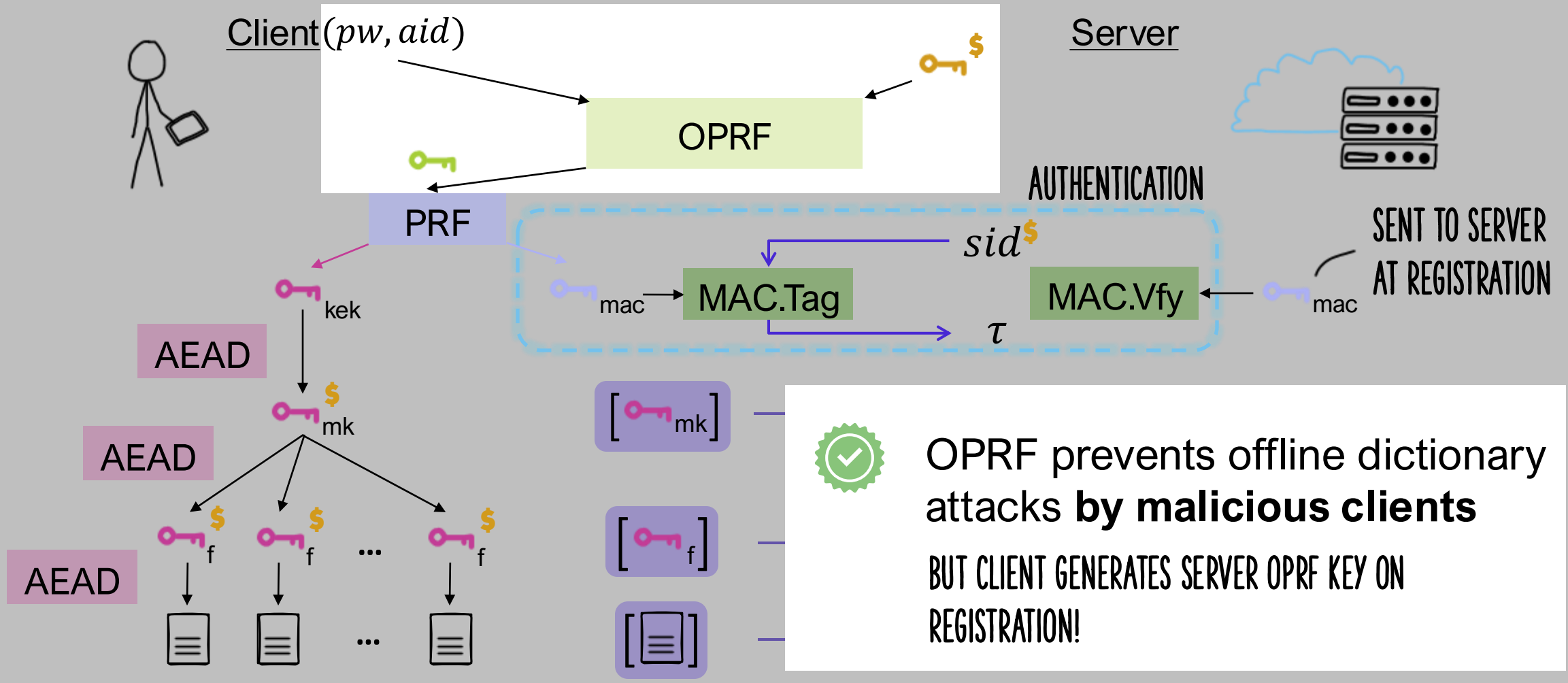
MAC

for user authentication

CSS: Authentication & File Encryption



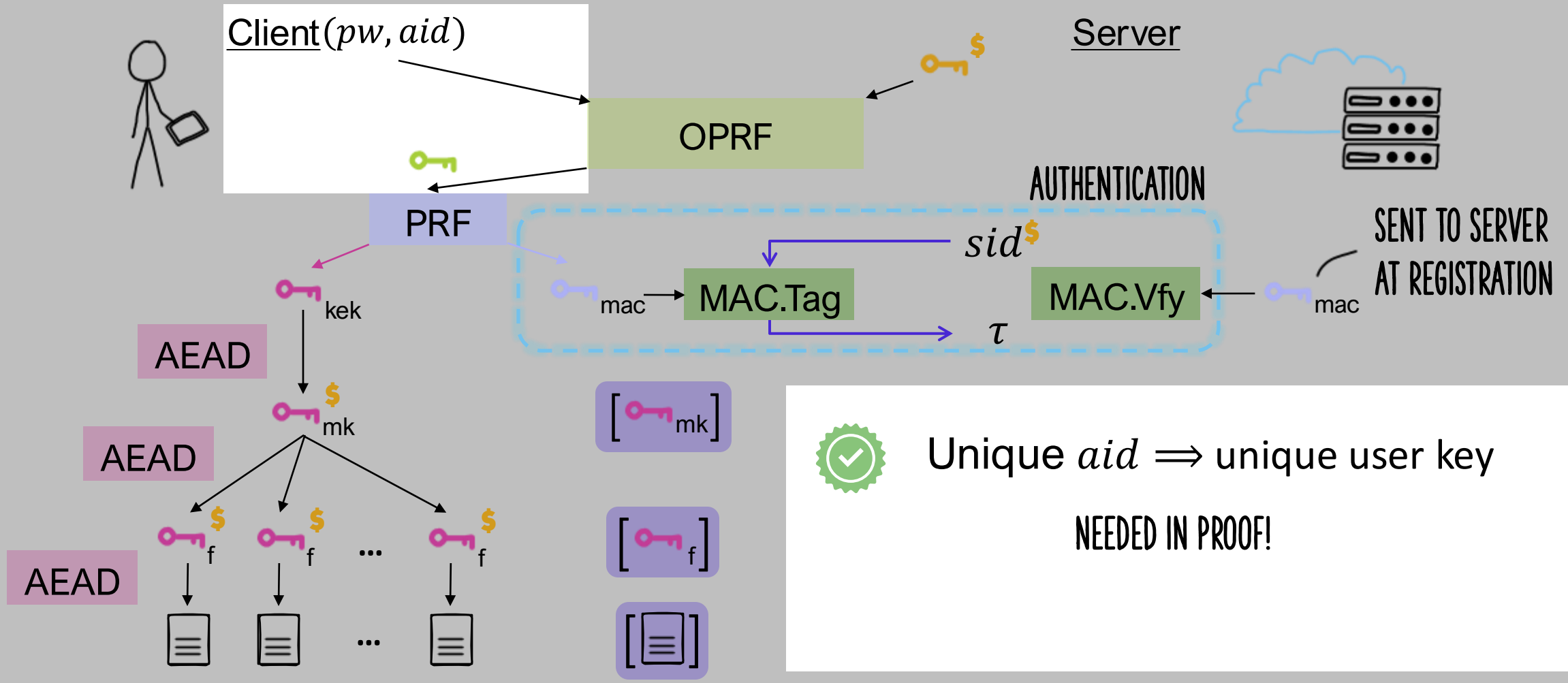
CSS: Authentication & File Encryption



OPRF prevents offline dictionary attacks **by malicious clients**

BUT CLIENT GENERATES SERVER OPRF KEY ON REGISTRATION!

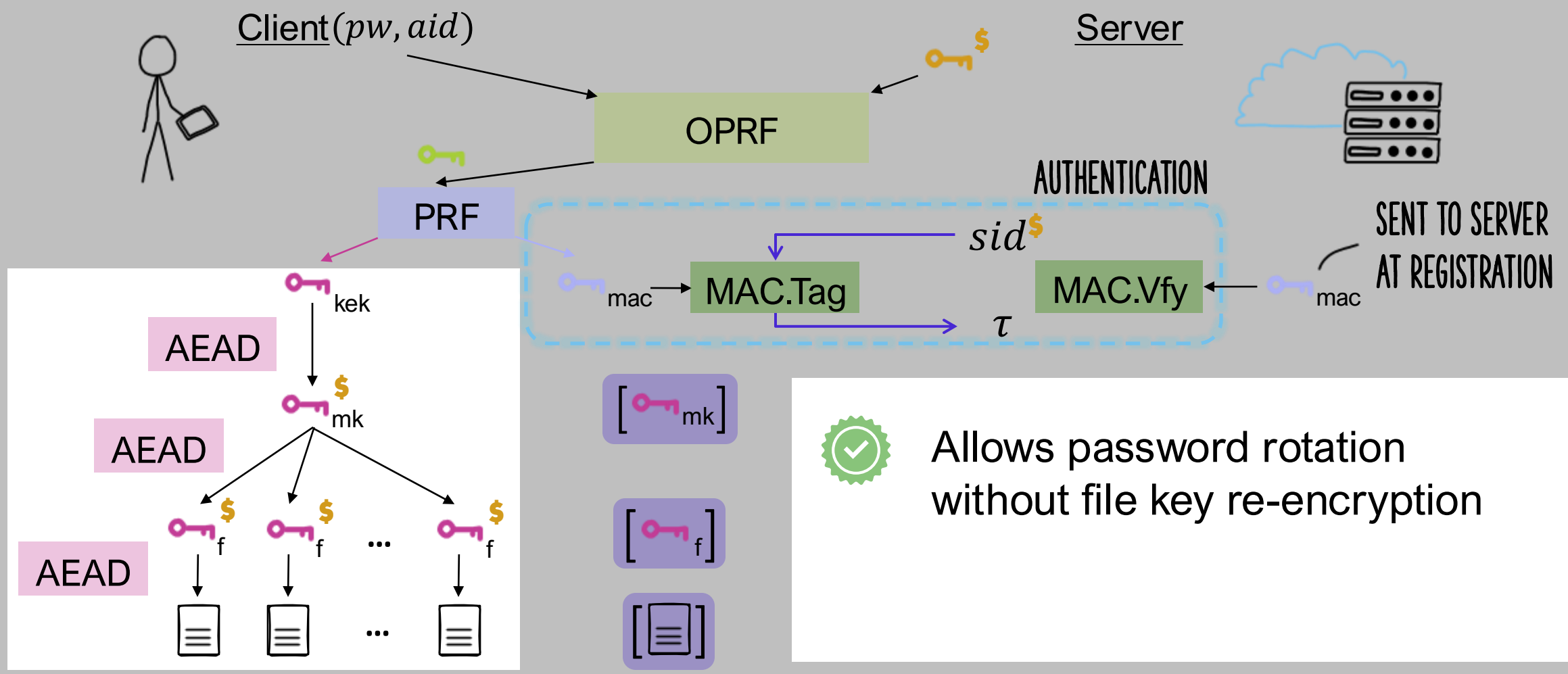
CSS: Authentication & File Encryption



Unique $aid \Longrightarrow$ unique user key

NEEDED IN PROOF!

CSS: Authentication & File Encryption



Allows password rotation without file key re-encryption

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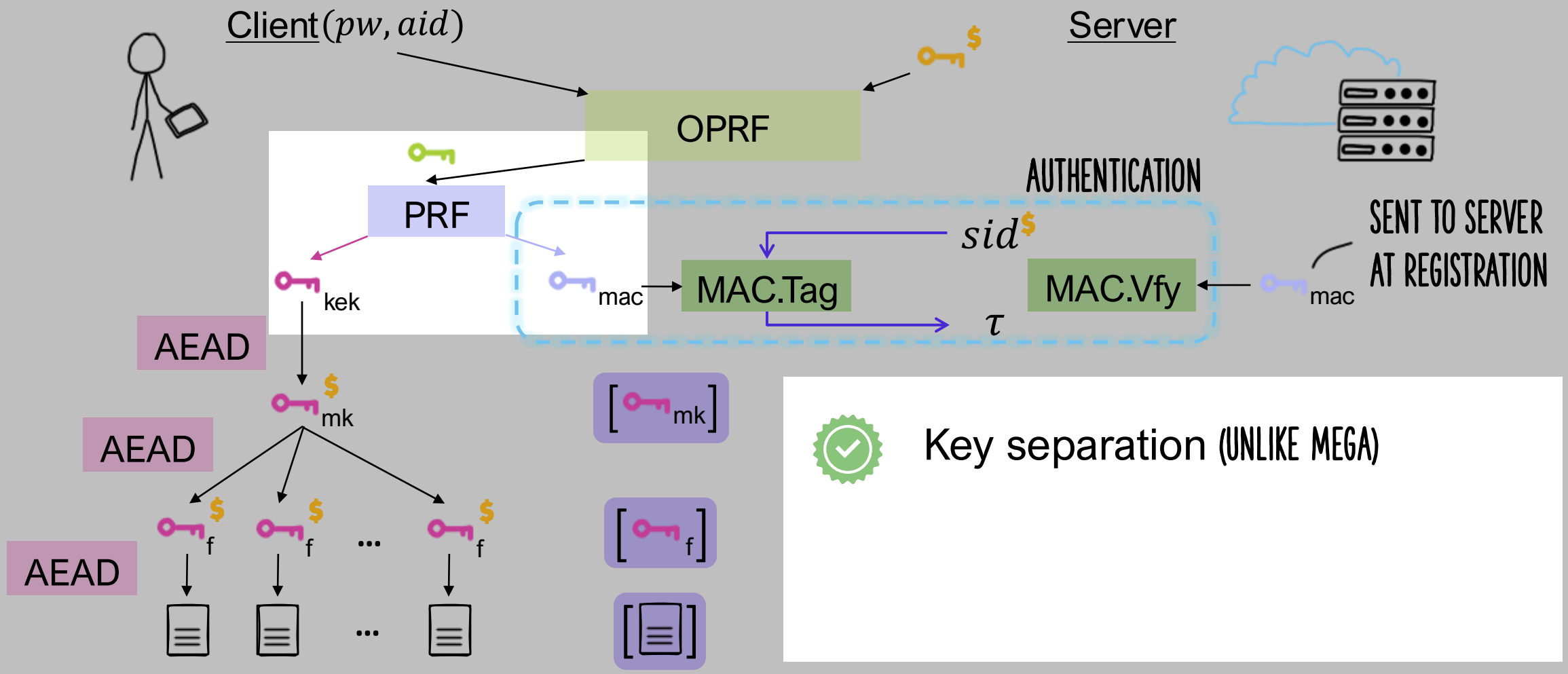
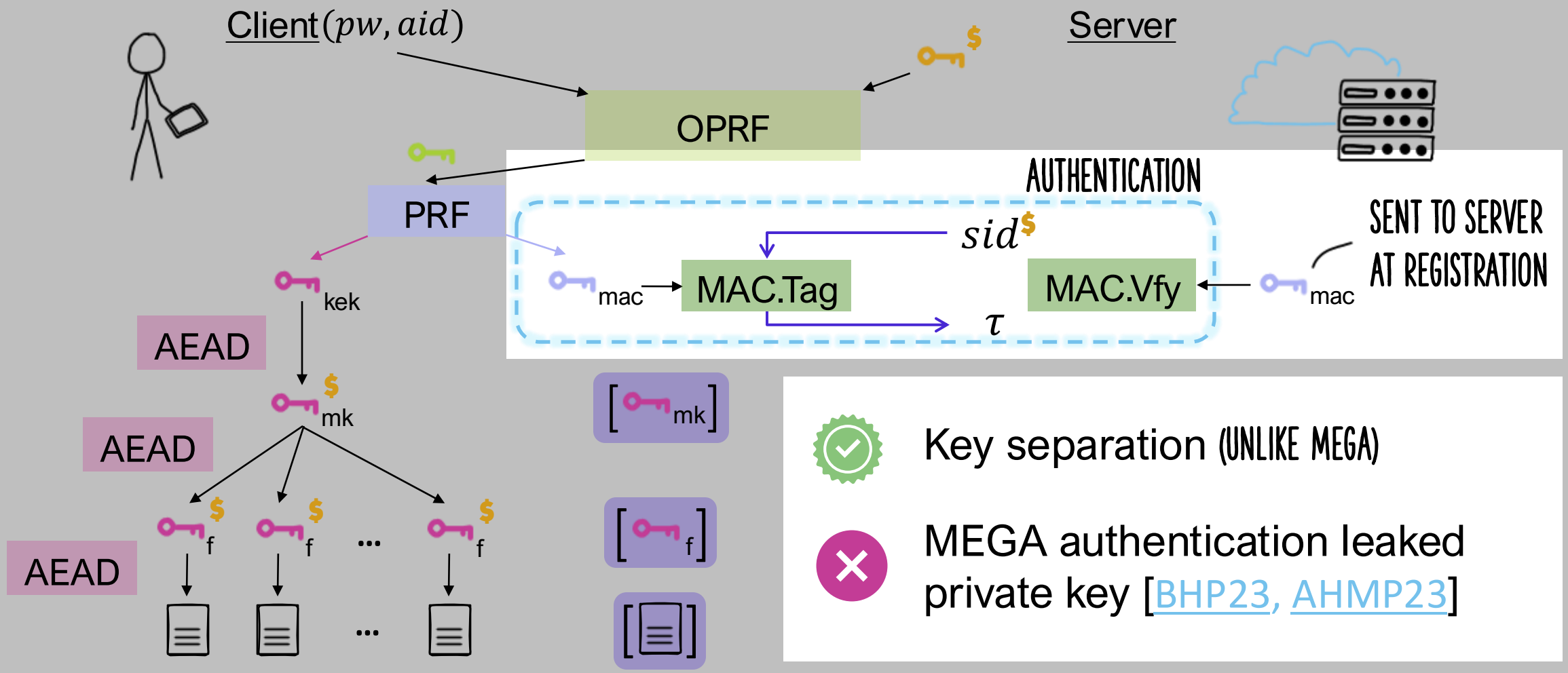
CSS: Authentication & File Encryption



Key separation (UNLIKE MEGA)

CSS: Authentication & File Encryption



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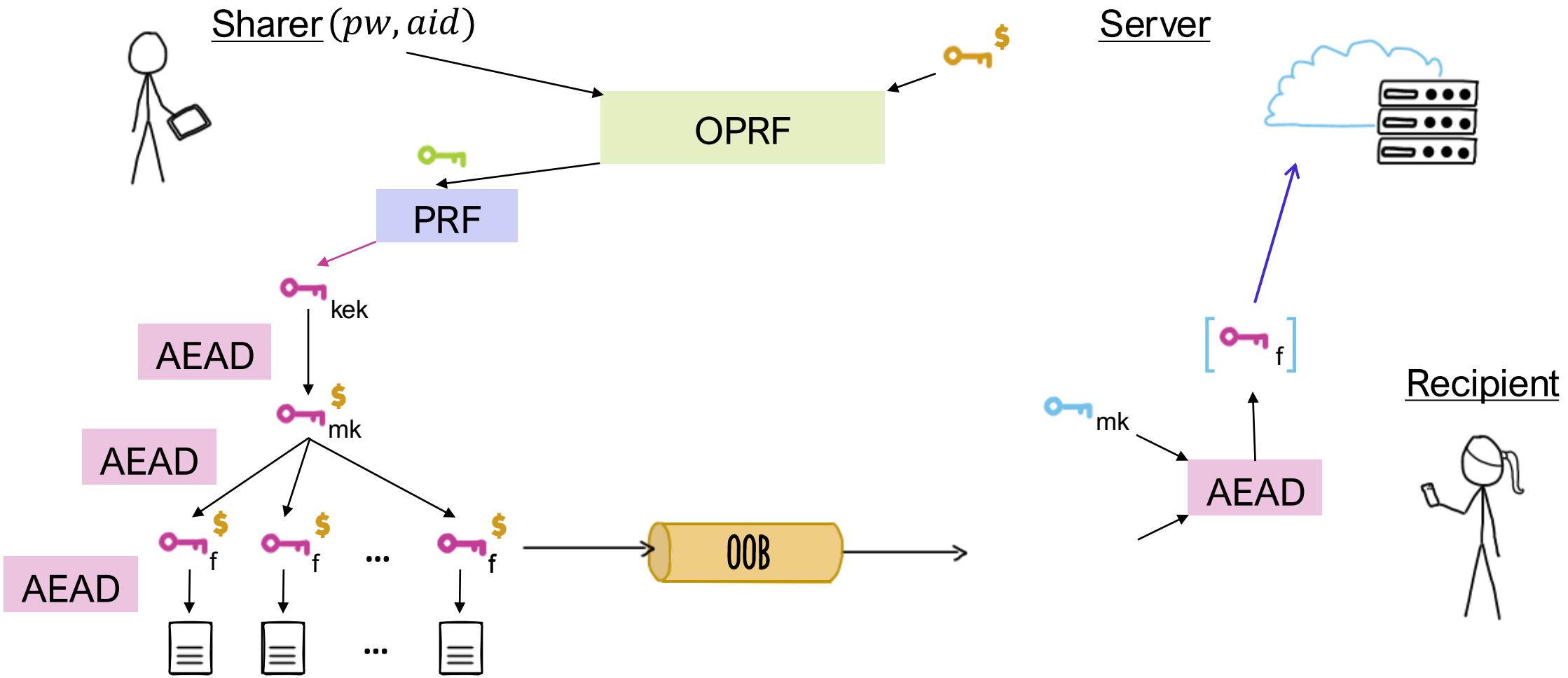
CSS: File Sharing



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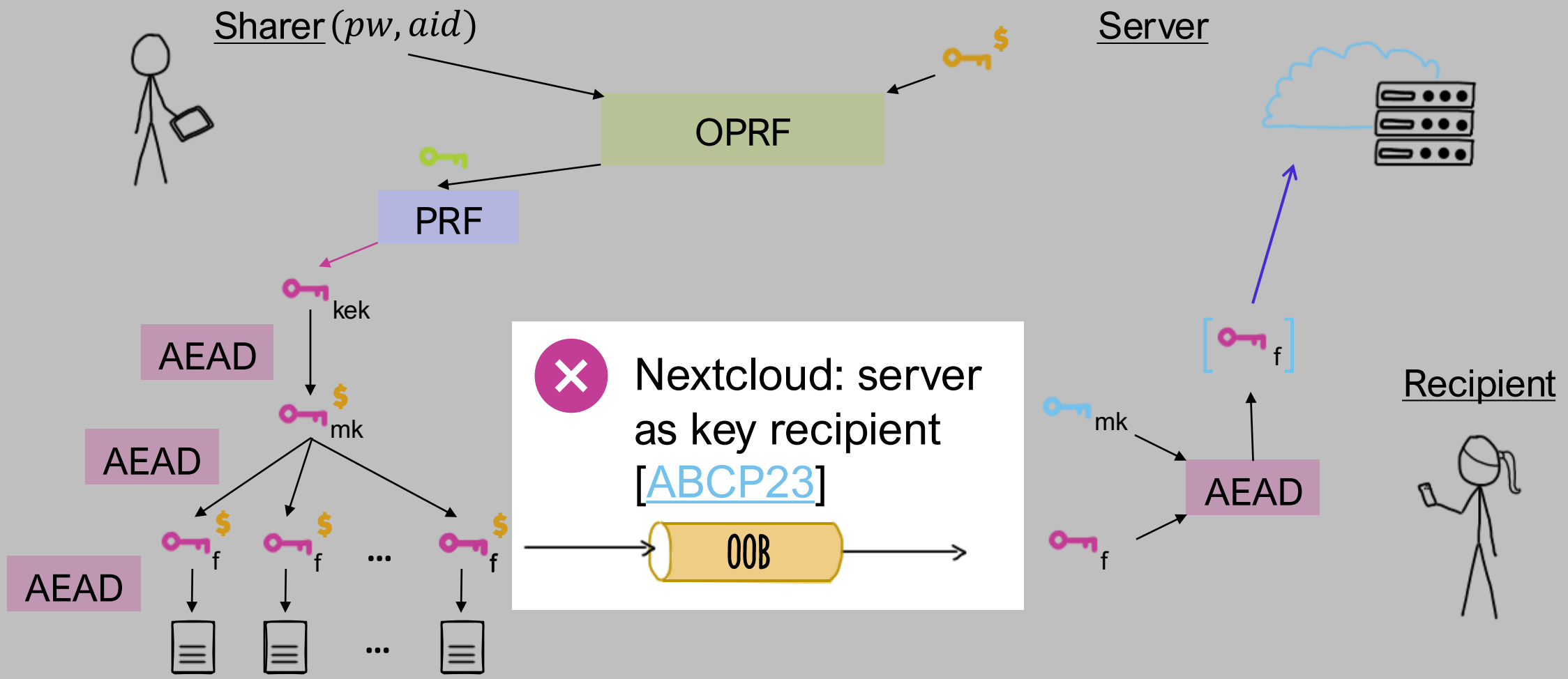
CSS: File Sharing



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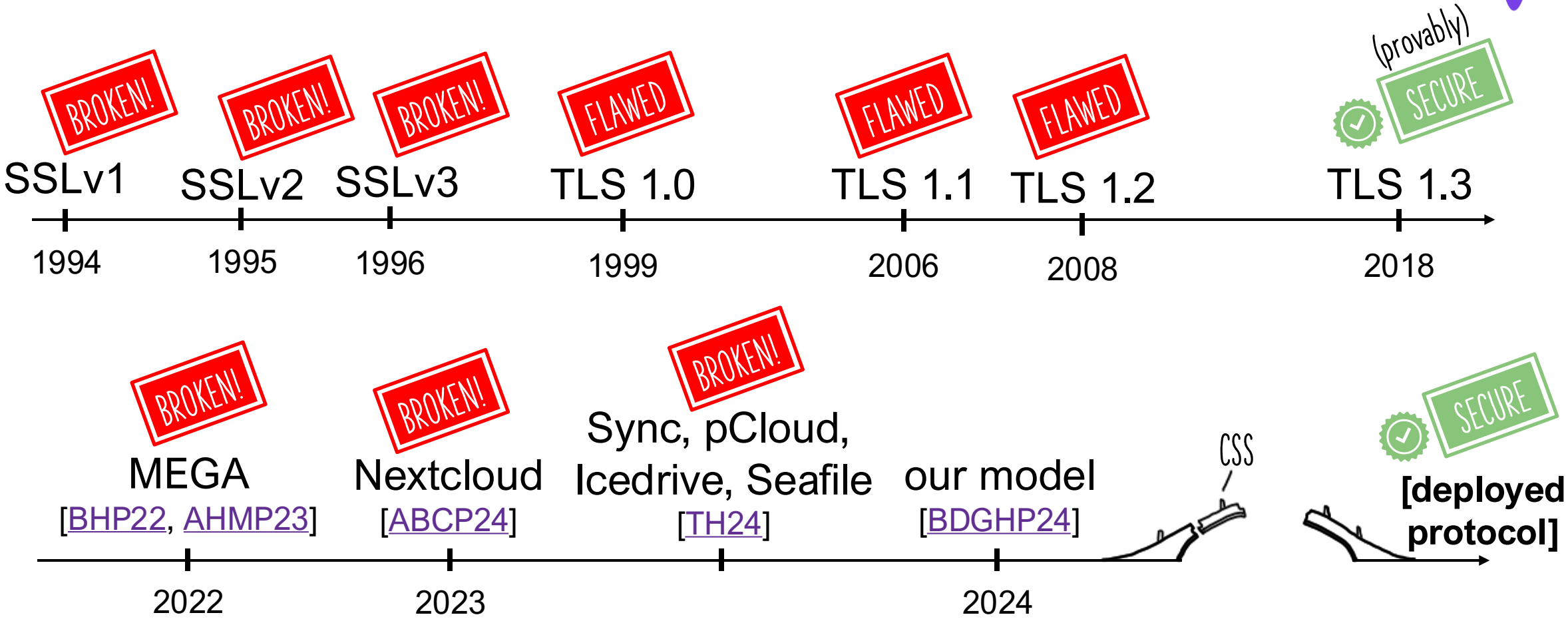
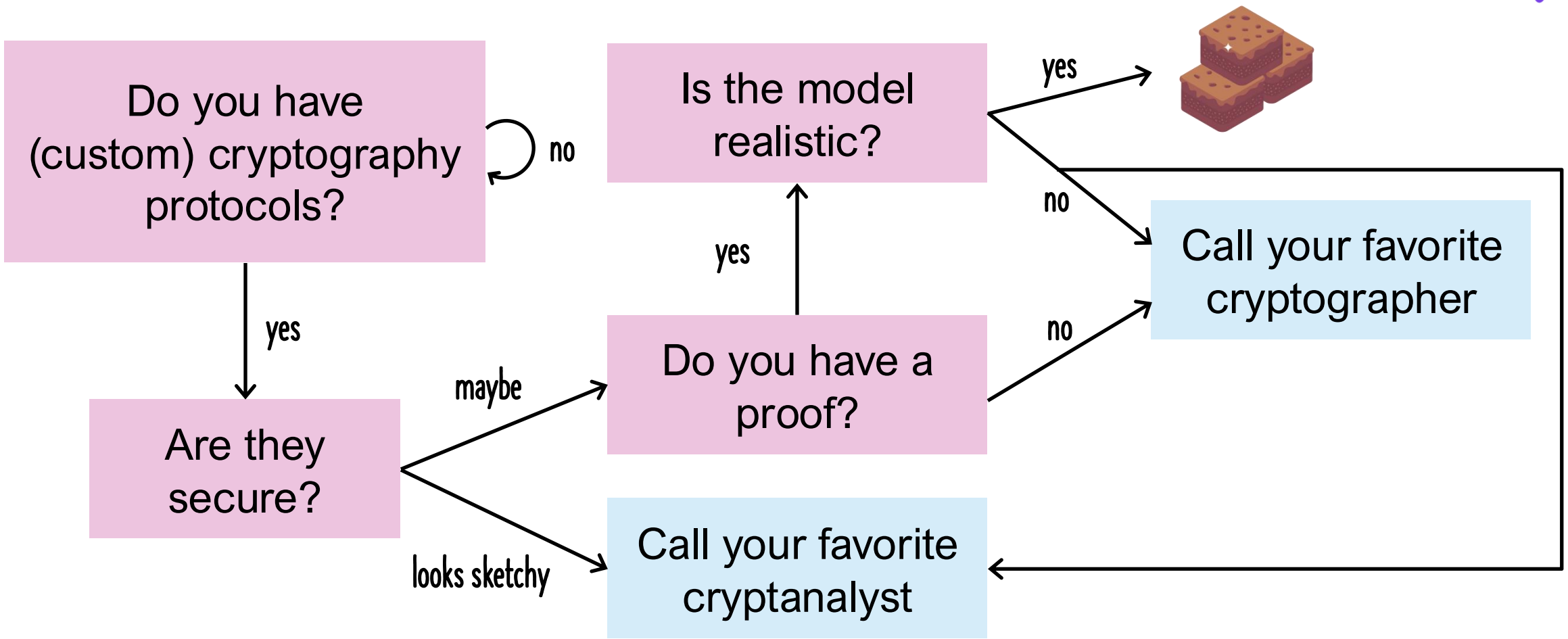
Why Provable Security Is Important

Provable Security



APPLIED

~~Apply~~ Cryptography



Brownie from flaticon

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eprint.iacr.org/2024/989

Joint work with:

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